# 1

# An Overview of Machine Design

## 1.1 Introduction

### 1.1.1 Machines and Machine Elements

A machine is a device that employs power to accomplish a desired function to benefit humankind. It is generally composed of a power source to provide power and movement, and an executive device to fulfil intended function. In between is a transmission system and controller. Power sources can be prime movers, that is, a machine utilizes a natural source of energy to produce power, like an internal combustion engine; or a secondary mover, like an electric motor, which receives energy directly or indirectly from a generator driven by a prime mover [1]. Take a car as an example; power sources, either engines in motor vehicles or batteries in electrical vehicles, provide power to executive devices; for example, wheels, through a transmission system (including couplings, clutches, shafts, powertrain etc.). The control system, that is, steering systems and brakes, control car movement. Lights, meters and windscreen wipers are accessories that facilitate a car running properly.

Machines involve a vast variety of mechanical products in various fields of manufacturing, transportation, aerospace, construction, agricultural, energy and many others. 'Products' covers industrial robots, machine tools and automated assembly systems in manufacturing systems; automobiles, trains, ships and aircraft in transportation vehicles; mobile cranes, dump trucks and concrete mixers in construction equipment. Household appliances, like vacuum cleaners, washing machines and air-conditioning systems are also machines.

A similar concept, that is, mechanism, is a combination of elements formed and connected to transmit motion in a predetermined fashion. Typical mechanisms include linkages, cams and follower systems, gears and gear trains and so on. There is no clear division between mechanisms and machines. If the transmitted forces or power are significant, it is considered a machine; otherwise, it is considered a mechanism [2]. Machinery is a derived term and refers to a grouping of mechanisms and machines [1].

A machine composes individual machine elements properly designed and arranged to work together. Machine elements are the fundamental components of a machine, and are broadly classified as universal elements, such as bolts, keys, splines, pins, belts, chains, gears, bearings and springs that are widely used in different kinds of machines, and special elements such as turbine blades, crankshafts and aircraft propellers, which

*Analysis and Design of Machine Elements,* First Edition. Wei Jiang.

Companion website: www.wiley.com/go/Jiang/analysis_of_machine_elements

perform specific functions [3]. This book focuses on the analysis and design of universal machine elements.

### 1.1.2 The Scope of Machine Design

Design is widely considered to be the central or distinguishing activity of engineering [4]. It aims to create and execute a purposeful plan to meet commercial, industrial and social needs. When design is discussed in mechanical engineering domain, especially about mechanical products or machines, it is termed mechanical or machine design.

Machine design is the art of envisioning, creating and developing a brand new or improving on an existing mechanical device for the fulfilment of human needs, with due regard for resource conservation and environmental impact [1, 5]. It is an innovative, iterative, decision making and problem-solving process involving comprehensive utilization of scientific knowledge and creative capability. Designers are required to generate concepts and decide deterministic dimensions for devices or products from limited information, ambiguous and sometimes even partially contradictory requirements to achieve users' objectives while satisfying a set of specified constraints. Therefore, the initial design is usually tentative. With more variables gradually determined, material, geometry, as well as manufacturing and tolerance details are fine-tuned during iteration until final optimum design is achieved [5].

Machine design generally has more than one solution. Since design is a rational process of choosing among design alternatives [6], it greatly depends on the designer's knowledge, previous experience, design method and design philosophies to solve a specific problem. Consider, for example, the design of an automobile. A large number of models are available on the market, and all of them can fulfil the function of transportation. The differences among them are the operation convenience, comfort, aesthetic appearance, cost and so on. These features decide the competitiveness and sales of products.

Analysis and design are indispensable aspects in the process of machine design. Analysis is concerned with predicting the response of an existing or a tentatively designed machine under specified inputs, which is especially important in creative design process; while design attempts to decide the dimensions and shapes of machines to meet performance requirements. Integrating analysis and design skills during the design process distinguishes an outstanding design engineer from a good one [7]. Since design is an evolutionary process, a tentative design is firstly proposed and then analysed to see if it satisfies the given specifications. If not, which is the usual case; the tentative design is revised with changes involving geometry, material and loads, and is analysed again until it satisfies the specified design requirements.

Extensive multidisciplinary skills and knowledge are employed in the design process to convert inadequate, vague requirements into a product that is functional, safe, reliable, manufacturable, competitive and marketable. Engineering science includes mechanics of solids and fluids, materials science, manufacturing processes and so on. Designers are required to use computers and graphics tools to visualize design plans. Since designers often work collaboratively on teams, communication skills, teamwork ability and presentation skills are equally important.

To design a machine or machine element successfully, design engineers not only need to develop competence in understanding and applying scientific knowledge, empirical information, professional judgement and ingenuity in solving practical problems, but also cultivate a strong sense of responsibility and professional work ethic. Mechanical design involves almost all the disciplines of mechanical engineering [8–10]. The extensive knowledge and skills required for a mechanical designer are briefly summarized as:

- Competence in mathematics, statics, dynamics, mechanics of materials, kinematics and mechanisms to facilitate load, stress and strength analyses; an advanced CAD/CAE (computer-aided design or engineering) or FEM (finite element method) technique is preferred;
- Familiar with engineering materials and their properties, materials processing, heat treatments and manufacturing processes;
- Knowledge of tribology, fluid mechanics, heat transfer, electrical and information technology and controls;
- Creativity, complex problem-solving capability and project management skills;
- Competence in graphical representation by sketches, engineering drawing, CAD tools and 3D visualization to convert mental design concepts into technical drawings;
- Both verbal and written communication skills and presentation skills to articulate design projects, describe constraints and limitations and present proposals and technical reports;
- Teamwork and collaboration capability, and a sense of social and ethical responsibilities.

Students are expected to appreciate that machine design is an integration of physical and engineering considerations with social concerns, with an aim to design machines with satisfactory lives and high reliabilities. With the globalization of business world, future design engineers are expected to feel comfortable to work in a vibrant and multicultural environment, learn to satisfy the needs of customers in a competent, responsible, ethical and professional manner and able to communicate complex aspects of design verbally and graphically to other members in both national and international concurrent design teams.

## 1.2 Machine Design

### 1.2.1 Machine Design Considerations

An important assessment of design quality is machine's safe and reliable performance of its intended function for the prescribed design life without serious breakdown. Besides, machine design involves a multitude of considerations, as summarized in Table 1.1. It is unrealistic to satisfy all these considerations, as some are seemingly incompatible. Designers are challenged to recognize incongruities and find compromises between these discrepancies. During the design process, the total life cycle of a product, from initial ideation, design, manufacturing, assembly to service and final disposal, should be reviewed, and situations that may practically occur during manufacturing, transporting, storing, installing, servicing and disposal be evaluated. The main concerns selected from Table 1.1 are discussed next and will be addressed throughout the book.

Apart from proper functioning, successful design of competitive machines must prevent premature failures to ensure safe and reliable operation throughout design lifetime. Traditional safety considerations for an element include strength, deflection and

**Table 1.1** Machine design considerations.

| **Functional considerations** | **Safety and reliability considerations** | **Manufacturing considerations** | **Form considerations** | **Economic, ecological, societal considerations** |
|---|---|---|---|---|
| Functionality | Load/stress/strength | Materials and properties | Geometry | Marketability |
| Operation | Deflection/rigidity | Heat treatments | Dimensions | Cost |
| Controllability | Friction/wear | Manufacturability | Volume | Recycling |
| Utility | Corrosion | Assembly and disassembly | Weight | Ecology |
| Efficiency | Stability | Packaging and transportation | Surface | Ergonomics |
| Kinematics | Noise and vibration | Maintainability | Styling | Liability |
| Lubrication | Durability/life | | Aesthetics | Cultural/Social impact |

stability; while for an element surface, the safety concerns are friction, wear, frictional heat and corrosion. Designers are required to anticipate potentially failure modes under various operating conditions and integrate safety into design process wherever possible. The design philosophy is first to take precaution against failure, but if failure does occur, the design must have a remedy to prevent catastrophic disaster [10].

Manufacturing changes the shapes and sizes of raw materials into the geometry of final elements specified by designers. Currently available manufacturing processes include casting, welding, forming, machining and additive manufacturing. Each process has its own attributes concerning processing power, time, cost and final product qualities. Factors considered while selecting manufacturing process include the geometry and properties of both raw materials and finished elements; and the quality requirements of finished elements, like tolerance, surface finishes, strength and so on. Besides, the number of elements to be produced, the cost, time, energy requirement and environmental impact also need to be considered [8–10].

The decisions on material, manufacturing process and design are interrelated with each other, and therefore should be considered integrally at the early stage of design. These considerations should also cover the whole life of an element, that is, from blank of raw material to manufacturing, heat treatments, assembly, maintenance and final disposal. For example, a large batch production of casted complicated heavy elements should keep the section with uniform thickness to avoid casting shrinkage; the number of machining planes should be reduced to minimize the number of fixtures; if an element needs heat treatments, use fillets rather than sharp corners; to facilitate assembly and disassembly, fittings and locating also need to be paid special attention.

Cost plays an important role in design decision making. Costs spent on product development include expenditures on materials, labour and material processing. Costs of materials and labour increase yearly, while costs of material processing depend on manufacturing processes, machine tools, quantities, required tolerances and so on. The larger the quantities and tolerances, the lower the manufacturing costs. Whenever possible, standard or purchasable products readily available from the market, such as contact bearings, fasteners, keys, motors, pumps and so on, are the first choice. In such cases, all designers need to do is to determine and provide preferred sizes and specifications.

Although, the basic objective of mechanical design is to provide a machine or device that benefits humanity, the consideration of ecological cycle or sustainable growth has become an increasing concern [11]. In the proposed design, recyclable materials are preferred. The selected material processing should have minimal energy consumption and reduced environmental pollution. Efficient material usage is also an important aspect for sustainable development. Light weight design and 3D printing are examples of effective material usage. In short, environment and resource concerns during manufacture, operation and disposal must be seriously taken into consideration.

During machine design, ergonomics or the man-machine relationship has gained increasing attention. Its aim is to ensure that machines are designed to accommodate operators with safety, comfort and efficiency. By incorporating human factors into design, product efficiency and safety can be improved and potential operational problems and product liability can be reduced.

Since designers and manufacturers are legally liable for any damage or harm from products, they have great responsibility to ensure high quality and safe operation of products, and should provide adequate warnings and instructions for use in the product specifications [8].

### 1.2.2 Machine Design Process

Machine design aims to produce a useful product satisfying the needs of customers. The design of a machine is inherently a complicated and delicate process, involving interactive and iterative procedures, complex calculations and countless design decisions [8]. To develop a safe, efficient and reliable product with excellent functionality and high competitiveness, proper design procedures and approaches should be established and followed. Figure 1.1 outlines a complete product development process currently employed.

The development of new machine from inception through elaboration to termination can be broadly classified into four stages: planning, concept design, detailed design, manufacturing and commercialization [8, 9]. The tasks and focus of each stage are introduced next.

1. Planning

   Design starts with the recognition of needs. The desire or expectation for a new product may be acquired from a target market, from dissatisfaction with existing products or from a particular adverse circumstance; for example, a need for a robot to work in hostile environment.

   The vague or subjective needs are then translated into detailed quantitative specifications to definite the function of the expected product. These specifications are the input and output quantities, such as power, operating speeds, expected life or safety, space or weight limitations.

   Financial investment, estimated price, cost targets, expected profits and other business issues, together with sales operations and time schedules also need to be considered at this stage.

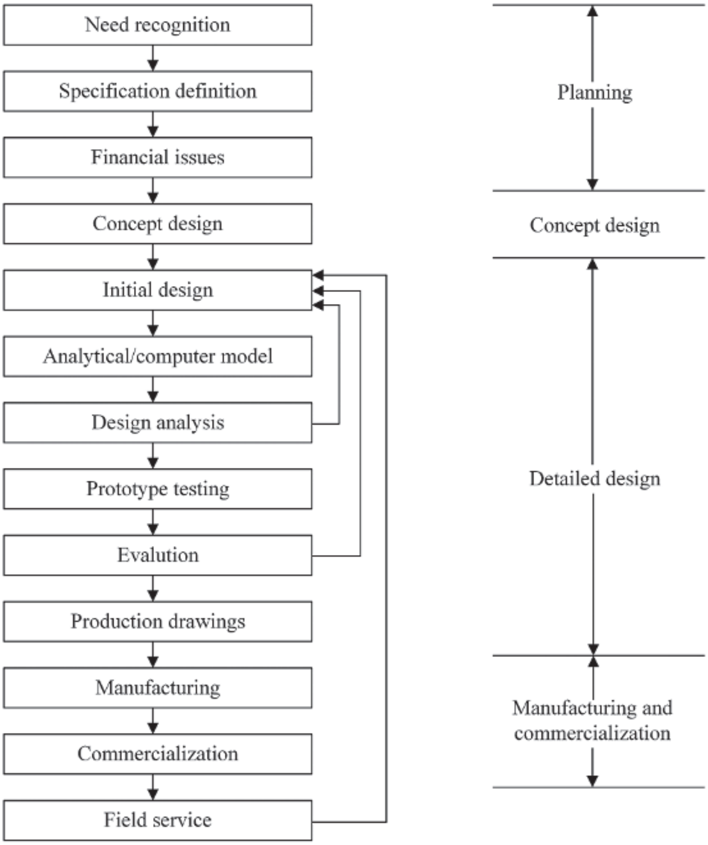

**Figure 1.1** Product development process.

2. Concept design
   Based on the simplified assumptions and previous experiences, a designer or a design team may propose several possible alternative concept designs satisfying function and design specifications. These proposed concept designs are investigated, quantified, compared, weighed and ranked in terms of established evaluation criteria, which gives desirable qualitative characteristics of a design according to the function statements and design specifications. The optimum concept design is then decided and will be designed in depth to meet specified criteria of performance, life, weight, cost, safety and others.
3. Detailed design
   Once the optimum concept design is determined, an initial design is proposed and developed into an analytical model or a computer model for pertinent analyses as required, including kinematic, force, strength, rigidity, heat transfer and so on. If analytical results are not satisfactory, designers return to the initial design to revise the previous tentative design. Otherwise, a physical prototype will be built, tested and evaluated. Evaluation criteria can refer to the considerations of machine design listed in Table 1.1. Based on the results of test and evaluation, the tentative design may be judged ready for manufacturing or may be revised and a second analytical

model and prototype built and tested. Since design is an evolutionary process, this iterative process is not unusual. After reiterations of analysis, optimization and evaluation, an optimal solution is finally achieved. The initial tentative design is converted into a workable product, and a set of detailed production drawings and design documents are produced to facilitate manufacturing. At this stage, potential manufacturing, assembly and maintenance issues also need to be considered.

4. Manufacturing and commercialization
   Once the initial design has been converted into the workable product successfully, practical manufacturing is organized to produce products. A full-scale production can be launched and products can be sold to customers by both domestic and global markets. Commercialization also involves customer service and especially warranty. Finally, service data on failure modes, failure rates, maintenance and safety problems are collected for future product improvement.

   In summary, machine design process includes the first three parts of comprehensive product development process. It aims to reach a compromise through repeated revision of initial design to fulfil design function, to satisfy design requirements and practical limitations. The primary focus of this book is on this part of design process, with proper consideration on manufacturing, material selection and heat treatments where necessary.

## 1.3 Machine Element Design

### 1.3.1 Machine Element Design Considerations

Machine element design is the design of mechanical elements or components. It is a more focused and an integral part of machine design, consisting of capacity calculation and structural design. Machine element design employs similar knowledge and skills to machine design. Since machine elements are the fundamental components of a machine, each element must be properly designed to facilitate its integration into a machine.

Machine element design must ensure efficient and safe function, with an appropriate combination of size, shape and material to withstand operating loads for the expected service life at minimum costs. The considerations of machine element design are similar to those of machine design, with more concerns on safety, manufacturability, costs, codes and standards.

The safety and reliability of individual machine elements decide the overall safety and life expectancy of a machine. The analysis, prediction and prevention of failure form the basis for the design of machine elements. In the design process, potential failures are prevented by proper material selection, reasonable assumption and simplification of operating loads, correct shape and dimension determination through accurate strength, rigidity and other relevant analyses.

Manufacturing produces elements to the desired dimensional accuracy and surface finish. Since manufacturing process affects final specifications of overall geometry, dimensions, tolerances or surface finishes, proper tolerances and acceptable surface finishes must be specified on design drawings to facilitate manufacturing process selection [8]. Normally, small tolerances and smooth surfaces increase manufacturing cost dramatically. Proper clearances and fits also need to be defined for mating elements.

In general, a compact design is preferred. After calculation, standard sizes close to the minimum acceptable dimension are usually specified for standardized elements, like fasteners, keys and rolling contact bearings. Through the selection of standardized elements, uniformity of practice and reduced cost are achieved.

### 1.3.2 Common Failure Modes in Machine Elements

A mechanical failure refers to the incapability of a machine or an element to perform its intended function [9]. It may arise from poor design detailing, inadequate material properties, manufacturing deficiencies, hostile service conditions and more often their interactions. A trivial oversight of any of these aspects may cause large detrimental and even catastrophic failure, resulting in serious financial, insurance and legal repercussions [12].

Mechanical failure modes commonly observed in industrial practice include deformation, yielding, fracture, fatigue, pitting and spalling, wear, scoring, scuffing, galling and seizure, corrosion, fretting, creep, buckling and so on.

Deformation includes elastic and plastic deformation, referring to the recoverable and unrecoverable deformation, respectively. When stresses generated in an element exceed yield strength, plastic deformation or yielding occurs. Both elastic and plastic deformation may cause malfunctioning of machine elements. A typical example is shafts supporting a pair of mating gears. The deformation of a shaft may prevent gears meshing properly, leading to interference, impact, wear, noise and vibration.

Fracture may occur in both brittle and ductile material due to either static or fluctuating loads. Ductile rupture occurs when plastic deformation reaches the extreme in ductile materials, leaving a dull, fibrous rupture surface; while brittle fracture happens when elastic deformation achieves the extreme in brittle materials, leaving a granular, multifaceted fracture surface [5, 13]. Fatigue fracture is a sudden and catastrophic failure, taking place due to the initiation and propagation of a microcrack under fluctuating loads over a period of time. The loads causing fatigue failure are usually far below the static failure level.

Surface fatigue failures are usually associated with rolling surface in contact. The repeatedly applied loads produce concentrated cyclic subsurface contact stresses. Micro-cracks initiate slightly below the contact surfaces and propagate until small bits of surface material spontaneously dislodge off the surfaces, producing surface pitting or spalling. Examples of pitting failure are manifested in rolling contact bearings, gear teeth and metal wheels rolling on rails. Pitted surfaces prevent proper function of elements, causing vibration and noise.

Wear is gradual removal of discrete particles from sliding contact surfaces, leading to a cumulative dimensional change on the element profiles. The most common types of wear are abrasive wear and adhesive wear. With an increase of severity of surface damage, adhesive wear is classified as scoring, scuffing, galling and seizure. Adhesive wear is the most common type of wear and the least preventable. The worn surface may impair element profiles, leading malfunction of machines. For instance, wear on gear tooth surfaces may cause intolerable noise and damaging vibration.

Corrosion occurs as a consequence of undesired deterioration of material as a result of chemical or electrochemical interaction with environment. It most happens to the machine elements exposed to corrosive mediums [5].

In summary, failure is the response of a machine or machine element to operating loads and service environments. Imperfection in design, materials and manufacturing may cause failure. Identification of possible failure modes under prescribed operating condition is an essential step in the early stage of machine element design. It is the designer's responsibility to predict, analyse and prevent prospective failure to ensure a successful design of machine elements or machines throughout a design's lifetime.

### 1.3.3 Design Criteria

Safety is always the paramount criterion in machine design [9], as catastrophic failures result in life losses, property destruction and environmental damage and must be prevented. To provide a safe, reliable and cost-effective machine element, it is essential to establish design criteria against potential failure modes. The design criteria commonly used against the previously discussed failure modes include strength, rigidity, life and wear criteria.

#### 1.3.3.1 Strength Criteria

Strength is the ability to resist loads. It is expressed in terms of ultimate strength, yield strength and fatigue strength [1]. Almost all kinds of failure modes, including yielding, fracture, fatigue, pitting, spalling, wear, scoring, scuffing, galling and seizure, are due to insufficient material strength to withstand loads. Design approaches must satisfy a strength criterion in the form of a stress-strength relationship, either within an element or on the element surface, to ensure safe design.

The strength criterion indicates that the actual stresses $\sigma$ acting on an element at a critical location under operating conditions must be less than the allowable stress of material $[\sigma]$, expressed as

$$\sigma \leq [\sigma] \tag{1.1}$$

The limiting condition to the right of the inequality depends on material properties. Under a static load, the allowable stress is the material strength divided by the allowable safety factor. The material strength is the yield strength in tension, compression or shear for ductile materials; and ultimate strength for brittle materials. Under a fluctuating load, the material strength is the endurance strength corresponding to the operating conditions. Detailed discussion about endurance strength will be introduced in Chapter 2.

The ability to quantify stress states at a critical location in a machine element is important for assessing failure possibility of an element. Stresses are obtained by simplified calculations according to various loading conditions. For uniaxial loading, the stress calculation is quite straightforward, using stress formula loaded by basic tension, shear or bending. For complex loading, a combined stress theory, either the maximum shear stress theory or the maximum distortion energy theory, is used to calculate multiaxial stresses [14, 15]. For contact loading, the contact stress is calculated by the Hertz formula [16].

Designers must ensure the maximum stresses at critical locations are less than material strength $\sigma_{lim}$ by a sufficient margin to guarantee adequate safety for an element. This margin is the factor of safety, a reasonable measure of relative safety of a load-carrying element. Thus, an alternate expression for strength criterion by safety factor $S$ is

$$S = \frac{\sigma_{\mathrm{lim}}}{\sigma} \geq [S] \tag{1.2}$$

Safety factors are employed to consider uncertainties and variabilities in loads, material strength, manufacturing qualities and operation conditions, as well as assumption in stress calculations. The selection of an appropriate value of allowable safety factor is based primarily on the these considerations, together with design codes and a designer's previous experience with similar products and conditions [8]. They should be carefully chosen to meet the required reliability at a reasonable cost. The allowable safety factor $[S]$ is generally within the range of 1.25–4 [8–10].

#### 1.3.3.2 Rigidity Criteria

Rigidity is the ability to resist deformation or deflection. It ensures accurate and precise operation of a machine. All machine elements deform under load, either elastically or plastically. Excessive deformation or deflection may cause interference between elements and premature failure due to vibration, wear and fatigue. When deflection is critical to safety or performance of an element the deflection must be analysed to satisfy rigidity criterion. Elastic strain, deflection, stiffness and stability are important considerations for the design of some elements.

Criteria for failure due to excessive deflection are often highly dependent on the application of machine. For example, machine tool frames must be extremely rigid to maintain manufacturing accuracy. Also, in a transmission, the shaft supporting gears must be rigid enough to avoid excessive deflection that may lead to gear disengagements. The following criteria are used to assess the rigidity of an element in different forms of deflection. When an element is subjected to a bending moment $M$, the deflection $y$ and slope $\theta$ should satisfy

$$y \le [y] \tag{1.3}$$

$$\theta \le [\theta] \tag{1.4}$$

When an element is subjected to a twisting moment $T$, the angular deflection $\varphi$ should satisfy

$$\varphi \le [\varphi] \tag{1.5}$$

Detailed calculation of deflection $y$, slope $\theta$ and angular deflection $\varphi$ depends on the cross-section geometry and loads, which can be referred to in *Mechanics of Materials* [14], or by finite element analysis for more complex geometries or loads. The allowable values of deflection $[y]$, slope $[\theta]$ and angular deflection $[\varphi]$ are selected by design requirements.

#### 1.3.3.3 Life Criteria

Normally, it is a requirement that the life $L$ of an element should be longer than the expected life $[L]$. Therefore

$$L \ge [L] \tag{1.6}$$

Detailed applications of life criteria can be found in Chapter 11 for the design of rolling contact bearings.

#### 1.3.3.4 Wear Criteria

Wear is the gradual removal of materials from contact surfaces as the result of relative motion of contacting elements. To against wear, the pressure $p$ between contact surfaces and relative sliding speeds $v$ must satisfy the following criteria,

$$p \leq [p] \tag{1.7}$$

$$pv \leq [pv] \tag{1.8}$$

Wear will be discussed in Chapter 8 for gears, in Chapter 11 for contact bearings and in Chapter 12 for sliding bearings where it will be the prime concern.

Other design criteria, including dynamic and reliability criteria, can be found in relevant references.

Mechanical failures, especially under variable loads, are strongly influenced by the interaction between design, manufacture and materials [12]. Although several design criteria have been established, the basic principles are the same; that is, comparing working conditions with allowable conditions. The allowable conditions largely depend on material properties, while the working conditions rely predominantly on design, manufacturing and operation.

Designers and manufacturers are liable for any damage or harm caused by product defects. Designers are responsible for preventing premature failure by good design, while manufacturers must ensure high quality products by using good quality control and comprehensive testing procedures.

### 1.3.4 Machine Element Design Process

In principle, the design process is similar for all kinds of machine elements, which intrinsically involves complex calculations, tradeoff decisions and iterative processes, through which an optimum design is obtained. Designs always demand enhanced performance, extended life, reduced weight, lower costs and improved safety [5]. Figure 1.2 presents a flowchart of a machine element design process to facilitate the development of a systematic approach.

The design process of a machine element can be broadly classified into four steps: design task identification, assumptions and decisions, analysis and evaluation and drawings and documentation. The tasks and focus of each step are introduced next.

1. Design task identification
   Broadly, it is required first to identify design requirements and design variables, the interactions of element with surrounding components and select the proper element type according to application and intended function.
2. Assumptions and decisions
   The material and heat treatment need to be selected first so that material property data required for the subsequent calculations can be collected from charts and tables in design handbooks. If required, an initial design for the element is proposed, showing tentative dimensions and shapes that may affect performance or stress analysis.

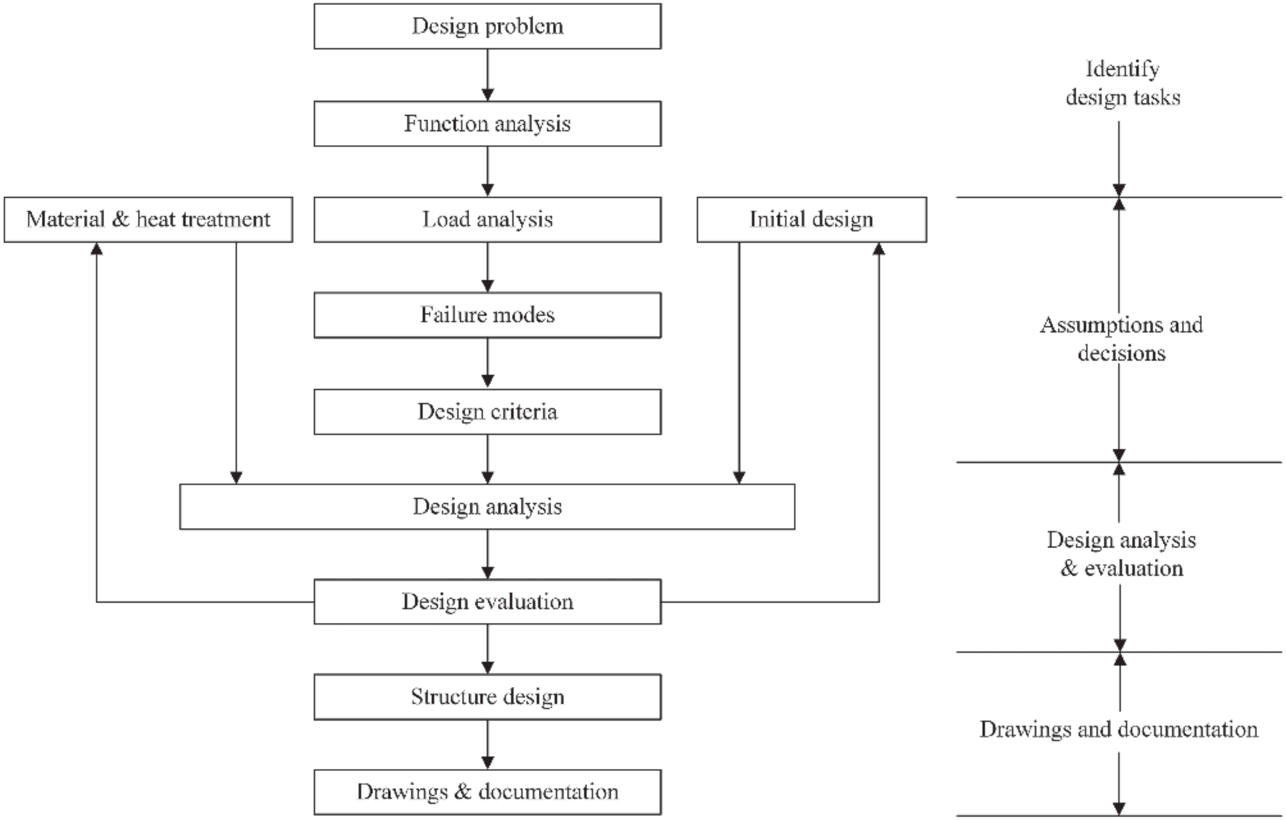

**Figure 1.2** Machine element design process.

The actual mechanical system needs to be idealized and simplified to facilitate load analysis. According to the loads and operating conditions, it is important to predict potential failure modes and decide on the corresponding design criteria.

3. Design analysis and evaluation
   According to the design criteria, perform strength or rigidity analyses to determine basic geometrical dimensions of machine elements that meet performance requirements against failure. The variability in manufacturing, assembly and service are considered by introducing modifying factors in the analyses. The calculated results need to be rounded up to standard or preferred dimensions.

   The performance of machine elements need to be assessed against material limits. A sufficient safety factor should be given to account for uncertainties and imprecision in the calculations due to idealization and simplification in design equations and data approximation. If the performance does not meet design requirements, which is the usual case, revise the previous initial design, dimensions or materials and then iterate the design process until the specified requirements, like desired design lifetime or design safety factor, are satisfied.
4. Drawings and documentation
   Once satisfactory results have been obtained, designers need to convert calculated dimensions to detailed drawings, considering manufacturing, assembly, maintenance and standardization. Design is implemented by a complete set of drawings and documentation with design specifications for all elements, including tolerances, fits and finishes. Standards, codes or preferred dimensions are usually incorporated to facilitate purchase and manufacture.

## 1.4 Materials and Their Properties

The selection of materials is an integral part of machine element design. The material selected for a specific machine element is determined by application requirements or, more precisely, by the requirement of material properties, such as strength, stiffness, reliability and durability. Additional factors, such as recyclability, environmental pollution and costs are also considered while selecting materials.

### 1.4.1 Types of Materials

Most machine elements are made from metals or metal alloys, such as steels, aluminium alloys and bronzes. Different numbering systems are employed to identify metal materials [8, 9]. Other materials, such as polymers, ceramics and composite materials, are also used in machine elements in various applications.

#### 1.4.1.1 Steels and Alloys

Because of the properties of high strength, high stiffness, durability and relative ease of fabrication, many types of steels are used in machine elements, including carbon steels, alloy steels, stainless steels, structural steels, tool steels and so on.

Steels, including carbon steel and alloy steel, are the most extensively used material for machine elements. Carbon steel is an alloy of iron and carbon with small amounts of manganese, silicon, sulfur and phosphorus. According to the content of carbon, we

**Table 1.2** Alloying elements and their effects on microstructure and properties [8–10].

| Added elements | Effects by adding alloying elements |
|---|---|
| Chromium | Forms various carbides of chromium with refined grain structure<br>Improves hardness, toughness and wear resistance<br>Increases strength at elevated temperatures |
| Nickel | Dissolved in ferrite without forming carbides or oxides<br>Increases strength without decrease ductility<br>Improves toughness, hardness and corrosion resistance |
| Manganese | Added in steels as a deoxidizing and desulfurizing agent<br>Dissolved in ferrite and forms carbides<br>Increases strength and hardness at proper amount |
| Silicon | Added in steels as a deoxidizing agent<br>Used with manganese, chromium and vanadium to stabilize carbides<br>Improves strength, hardness and wear resistance |
| Molybdenum | Dissolved in ferrite partially and form carbides, contributes to a fine grain size<br>Improves hardenability and high-temperature strength<br>Increases hardness and toughness |
| Vanadium | Dissolved in ferrite and easy to form carbides, hence is used in small amounts<br>Strong deoxidizing agent and promotes a fine grain size<br>Improves strength, toughness, keeps hardness at high temperature |
| Tungsten | Maintains hardness even at high temperature, widely used in tool steels<br>Produces a fine, dense structure<br>Similar effect to that of molybdenum, but needs greater quantities<br>Increases both toughness and hardness |

have low-carbon steels with less than 0.3% carbon, medium-carbon steels with 0.3–0.5% carbon and high-carbon steels with more than 0.5% carbon [9]. Carbon has a great effect on strength, hardness and ductility of any steel. Alloy steels have sufficient quantities of one or more elements other than carbon introduced to modify steel properties. Commonly added alloying elements include chromium, nickel, manganese, molybdenum, vanadium and many others. Their effects on the microstructures and steel properties are listed in Table 1.2.

Alloy steels have two types for special applications, that is, stainless steels and superalloys. Stainless steels contain a minimum of 10% chromium in three main types; austenitic, ferritic and martensitic stainless steels [9]. The most important characteristic of stainless steels is their resistance to corrosive environments.

Superalloys are primarily used for elevated temperature applications, such as in gas turbines, jet engines and heat exchangers. The most attractive properties of superalloys are the high temperature strength and resistance to creep, oxidation and corrosion [10].

Other types of steels are also available, such as structural steels and tool steels. Structural steels are basically low-carbon, hot-rolled steels in the form of sheet, plate and bar, and are usually used in construction and machines. Tool steels, as the designation implies, serve for making tools in manufacturing engineering.

### 1.4.1.2 Cast Irons and Cast Steels

Cast irons contain iron, carbon (between 2~4%), silicon and manganese [10]. Additional alloying elements are sometimes added to improve material properties. Cast irons have excellent machinability, hardness, wear resistance and damping capability, yet lower tensile strength.

The commonly used cast irons are white cast iron, grey cast iron, ductile and nodular cast iron, malleable cast iron and alloy cast iron. White cast iron is extremely hard, wear-resistant, brittle and hard to machine. Typical applications are found in extrusion dies and railway brake shoes. Grey cast iron has high compressive strength and good wear resistance, yet it is brittle and weak under tension and has poor weldability. Due to low cost and convenient batch casting, grey cast iron is widely used in engine blocks, machine bases and frames. Ductile cast iron, or nodular cast iron, has substantial ductility, improved tensile strength, stiffness and impact resistance. Typical applications include engine crankshafts and heavy-duty gears. Malleable cast iron is annealed white cast irons with high strength and elastic modulus, good machinability and wear resistance. Typical applications are railway equipment and construction machinery. Nickel, chromium and molybdenum are the common elements added in alloy cast iron. The addition of these elements increases strength, hardness, wear resistance and impact resistance [8–10].

Cast steels have the same alloying elements as wrought steels. Since the mechanical properties can be modified by heat treatment, cast steels are used for complex shaped elements requiring a high strength.

### 1.4.1.3 Nonferrous Alloys

Commonly used nonferrous alloys in machine elements include aluminium alloys, magnesium alloys, nickel alloys, titanium alloys, zinc alloys and copper alloys.

Aluminium alloys have both wrought and cast forms. The attractive properties of aluminium alloys are lightweight, good corrosion resistance, relative ease of forming and machining. They are widely used in structural and mechanical applications without strength requirements. Magnesium alloys are the lightest engineering metals, have a high strength-to-weight ratio and are widely used in aircraft and automotive industries.

Nickel alloys are used in applications requiring corrosion and oxidation resistance, high strength and toughness at temperature extremes as high as 1093°C or as low as −240°C [10]. Examples are turbine engine components, chemical processing equipment and marine components. Commercially available nickel alloys include Monel, Inconel and Hastelloy.

Titanium alloys have excellent corrosion resistance, outstanding strength-to-weight ratios and high-temperature strength. However, titanium alloys are expensive and have poor machinability. Typical applications of titanium alloys include aerospace and aircraft structures, marine components and human internal replacement devices.

Zinc alloys are inexpensive with moderate strength. They have low melting temperature and widely used in castings and zinc galvanizing. Typical zinc die-castings include automotive parts, building hardware and so on.

Copper alloys include brasses and bronzes. When copper is alloyed with zinc, it is called brass. Brass has excellent machinability and corrosion resistance and is used in tubing or piping, screw connections, locks, watches and so on. Bronze refers to copper alloyed with metals such as tin, lead, phosphor, aluminium, silicon, nickel. Wrought bronze alloys include phosphor bronze, leaded phosphor bronze, aluminium bronze and silicon bronze; while cast bronze alloys have tin bronze, leaded tin bronze, nickel tin bronze and aluminium bronze [9]. Bronzes are softer than ferrous alloys but have good strength, machinability and wear resistance. They run well against steel or cast iron when lubricated and can support high loads and operate at high temperatures. These qualities are utilized in sliding bearings and worm gearing where the combination of heavy loads and high sliding velocities places them in analogous situations [10].

#### 1.4.1.4 Polymers

Polymers, usually referred to as plastics, fall into two main groups; that is, thermoplastics and thermosets. Thermoplastics are softened with heat and include acetal, acrylic, acrylonitrile-butadiene-styrene (ABS), nylon, polycarbonate, polyimide and polyvinyl chloride (PVC). They are generally impact resistant. Thermosets are generally heat resistant, including epoxy, phenolic and polyester [9, 10]. Both types are inexpensive, light in weight, resistant to corrosion and wear. Also, they have a low coefficient of friction, low strength and provide quiet and smooth operation.

#### 1.4.1.5 Composite Materials

Composite materials are comprised of matrix materials and reinforcement materials. Each remains distinct and separate from each other. Matrix materials are various plastic resins like nylon, epoxy or polyester and metals, while reinforcements include glass, carbon and SiC (silicon carbide) in the form of continuous fibres, either straight or woven, short chopped fibres and particulates [8–10]. The reinforcement provides stiffness and strength, and the matrix holds the materials together and transfers load to the reinforcement materials.

Unlike isotropic, homogeneous engineering materials that have identical material properties in every direction, the material properties of composites vary with both location and direction. The orientation of multiple laminates can be optimized to reach a desirable high strength-to-weight ratio or high stiffness-to-weight ratio. Therefore, composite materials are becoming increasingly popular in automotive, marine, aircraft and spacecraft applications to realize lightweight design with high structural stiffness and excellent strength performance.

### 1.4.2 Material Properties

Material properties, including mechanical, physical, chemical, dimensional and processing properties, are important considerations in material selection. Among them, mechanical properties are especially crucial in determining the size and shape of machine elements. They also decide the performance of machine element under operating conditions.

Mechanical properties refer to strength, stiffness, hardness, toughness, ductility, impact, and creep and so on. Material strength considered for design calculation depends largely on the selected materials and loading conditions. For example, yield strengths are mainly applied to ductile materials; ultimate tensile strength for brittle materials; ultimate compressive strength for ceramics and glasses and fatigue strength for cyclic loading. Material stiffness is represented by the elastic modulus or Young's modulus and Poisson's ratio, which is almost the same for all steels [10]. The service

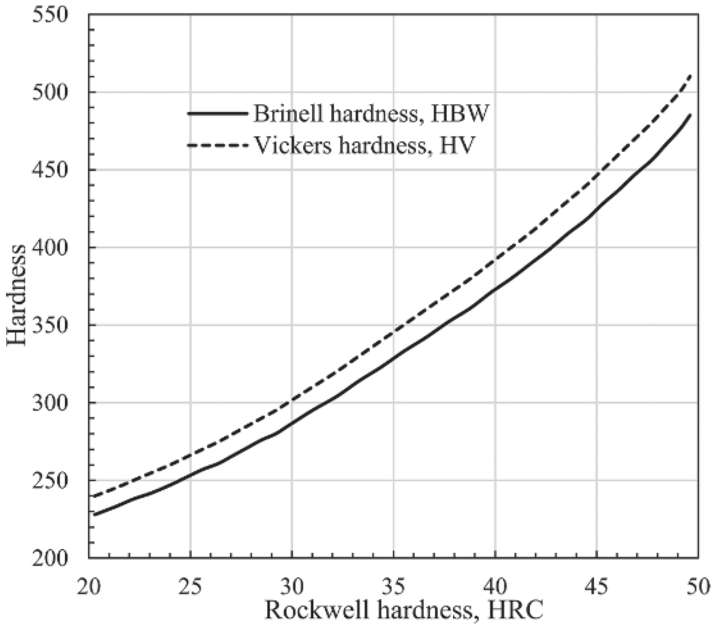

**Figure 1.3** Hardness conversions [17].

performance and failure modes have close relations to mechanical properties. For example, wear relates closely to the hardness of a material. The higher the carbon content, the greater the hardness of steels. Commonly used hardness definitions in machine elements are Brinell hardness (HBW or HB), Rockwell hardness (HRA/HRB/HRC, where A, B, C represent different scales) [8] and Vickers hardness (HV). The conversion from HRC to HV and HBW (300 kg load, 10 mm ball) is presented in Figure 1.3.

Physical properties refer to density, electrical, magnetic and optical properties, as well as thermal properties, such as thermal conductivity, thermal expansion, specific heat, melting point, flammability and so on. Chemical properties include composition, corrosion resistance, degradation, oxidation, embrittlement and so on. The consideration of chemical properties closely related to the operating environments of machine elements. Dimensional properties refer to the size, shape, surface finish, tolerances and appearance of raw materials or blank materials, which affect manufacturing costs. Processing properties refer to the materials' manufacturability; that is, capability for machining, casting, forming, welding and so on. Usually, ductile materials can be easily forged, rolled or drawn, while brittle materials should be shaped by other methods.

### 1.4.3 Heat Treatments

The final material properties are dramatically affected by heat treatments. Heat treatment refers to time-controlled or temperature-controlled heating and cooling processes with an aim to modify materials' mechanical properties. Commonly used heat treatments for steel machine elements include annealing, normalizing, quenching, tempering and case hardening.

During annealing treatment, the material is heated above the upper critical temperature and is held for a designated time until the composition becomes uniform. It is then cooled slowly in a furnace to a temperature below the lower critical temperature and continues to be cooled to room temperature outside the furnace [9]. Annealing produces a soft, ductile, low-strength material, free of significant internal stresses with a refined grain microstructure.

Normalizing is similar to annealing, except the material is heated above the upper critical temperature and cooled in still air to room temperature. Compared with annealing, the rapid cooling in normalizing produces harder steel with higher strength and a coarser grain structure. Normalizing is often used as a final treatment [8].

Through-hardening is accomplished by heating elements above the transformation temperature, followed by rapidly cooling within a quenching medium such as water or oil [9]. In the controlled cooling rate process or quenching, austenite formed above the transformation temperature is transformed into martensite; the hardest, strongest form of steel. The rate of cooling determines the amount of transformation and thus the hardness and strength.

Tempering is usually executed immediately after quenching. It involves reheating the hardened steel to a temperature below the transformation temperature range followed by a desired cooling to ambient temperature. The selection of tempering temperate depends upon the composition and the degree of hardness or toughness required. With increasing tempering temperature, tensile strength and yield strength decrease, whereas ductility improves [9]. The tempering process modifies the steel properties and relieves residual stresses.

Case hardening hardens material surfaces only. Case hardening includes carburizing, nitriding, cyaniding, carbonitriding, induction hardening and flame hardening processes. Carburizing or nitriding is based on the diffusion of additional carbon or nitrogen to some depth on the surface of already machined and heat-treated elements to achieve a high surface hardness. Induction hardening and flame hardening rapidly heat medium carbon or alloy steel element surfaces for a limited time so that a small, controlled depth of material reaches the transformation range then, upon immediate quenching and tempering, only the area above the transformation range produces the high level of martensite required for high hardness. Case hardening produces a great hardness on the outer surface, while retaining ductility and toughness in the core [8, 10].

### 1.4.4 Material Selection

The selection of materials is an important decision in machine element design. Satisfactory performance of machine elements and machines depends greatly on materials and their properties. Materials selection starts by referring to previous applications or similar experiences, the desirable material properties and the knowledge of physical, economical and processing properties of materials. Here are main points for material selection. A more detailed systemic approach can be found in reference by Ashby [18].

The required material properties are determined by service conditions, potential failure modes and so on. Service conditions could be fluctuating loads, corrosive environments or high temperatures. The required service performance relates to the corresponding material properties. Therefore, an element subjected to a fluctuating load should have high fatigue strength; an element working in a corrosive environment must have corrosion resistance. Analysing potential failure mode is also helpful for establishing required material properties for the element. For example, to resist against excessive wear, hard materials are required; to resist against large deformation, materials with large modulus of elasticity or stiffness are preferred.

Materials may be available in different forms. Proper manufacturing processes, that is, machining, forming, joining, finishing and coating, are required to turn original shaped materials into designed machine elements. Therefore, a material's capability for forming, joining or welding together with the initial material cost and processing costs are important considerations in material selection. Besides, recycling, disposal, legal and health issues are additional considerations [10].

After identifying, selecting, evaluating and ranking candidate materials, combined with making compromises among constraints of properties, availability, machinability and costs, a final selection decision can be made.

## 1.5 Unit Systems

A unit is a specified magnitude of a physical quantity [10]. Units chosen for any three quantities of force, mass, length, and time are called base units, the fourth unit is the derived unit. If force, length and time are base units, the system is a gravitational system of units, such as the foot-pound-second (fps) system and inch-pound-second (ips)

**Table 1.3** Commonly used design variables and their units.

| Variables | Symbol | SI units | ips units | fps units |
|---|---|---|---|---|
| Force | $F$ | N (newton) | lb (pound) | lb |
| Length | $l$ | m (metre) | in. (inch) | ft (foot) |
| Mass | $m$ | kg (kilogram) | lb $s^2$ $in.^{-1}$ | slug (lb $s^2$ $ft^{-1}$) |
| Time | $t$ | s (second) | s | s |
| Acceleration | $a$ | m $s^{-2}$ | in. $s^{-2}$ | ft $s^{-2}$ |
| Angle | $\theta$ | rad or degree (°) | rad (radian) or degree (°) | rad or degree (°) |
| Angular velocity | $\omega$ | rad $s^{-1}$ | rad $s^{-1}$ | rad $s^{-1}$ |
| Energy or work | $E$, $W$ | J (joule) | lb in. | lb ft |
| Frequency | $f$ | Hz (Hertz) | | |
| Moment or torque | $M$,$T$ | N m | lb in. | lb ft |
| Power | $P$ | N m $s^{-1}$ = W (watt) | lb in $s^{-1}$ | lb ft $s^{-1}$, hp |
| Pressure | $p$ | Pa (Pascal) | psi, lb $in.^{-2}$ | psf |
| Stress | $\sigma$, $\tau$ | MPa | psi, lb $in.^{-2}$ | – |
| Temperature | $T$ | degrees Celsius (°C) | degrees Fahrenheit (°F) | degrees Fahrenheit (°F) |
| Velocity | $v$ | m $s^{-1}$ | in $s^{-1}$ | ft $s^{-1}$ |
| Weight | $W$ | N | lb | lb |

**Table 1.4** Selected conversion relationships.

| Quantity | ips to SI conversion | Formula |
|---|---|---|
| Force | 1 lb = 4.448 N | 1 N = 1 kg m $s^{-2}$ |
| Length | 1 in. = 25.4 mm | |
| Mass | 1 lb = 0.454 kg | |
| Modulus of elasticity | $10^6$ psi = 6.895 GPa | |
| Moment or torque | 1 lb in = 0.1138 N m | |
| Power | 1 hp = 550 lb ft $s^{-1}$ = 745.7 W(watts) | 1 W = 1 J $s^{-1}$ = 1 N m $s^{-1}$ |
| Pressure | 1 psi = 6895 Pa | 1 Pa = 1 N $m^{-2}$ |
| Stress | 1 psi = $6.895 \times 10^{-3}$ MPa | 1 Pa = 1 N $m^{-2}$ |
| Work or energy | 1 lb in. = 0.1138 N m | 1 J = 1 N m |

system. If mass, length and time are base units, the system is an absolute system of units, such as the International System of Units (SI) [8]. The unit system used in this book is SI.

In engineering design, any set of calculations must employ a consistent system of units. Table 1.3 lists typical units associated with these systems and their standard abbreviations.

Sometimes a unit has to be converted from one system to another. Their conversion factors are listed in Table 1.4.

## 1.6 Standards and Codes

A standard is a set of specifications for elements, materials or processes formulated through a cooperative effort among industrial organizations, with an aim to achieve interchangeability, compatibility and uniformity for elements within a country or among cooperating countries [5]. The adoption of standards ensures high design efficiency by avoiding repetitive calculations, providing interchangeable elements on the spot with minimum downtime [1]. It permits convenient manufacture with standard machines and tooling.

Currently used standards are established by organizations or societies of various countries, such as the ANSI by the American National Standards Institute, BS by the British Standards Institute, EN by the European Committee for Standardization, DIN by the German Institute for Standardization, GB by the Standardization Administration of the People's Republic of China and ISO by the International Organization for Standardization. Other commonly used standards also include the AISI developed by the American Iron and Steel Institute, ASME by the American Society of Mechanical Engineers, ASTM by the American Society for Testing and Materials, SAE by the Society of Automotive Engineers and so on.

A code is a set of specifications for analysis, design, manufacture and construction [8]. Codes are legally binding documents, complied by a governmental agency, with an aim to achieve a specified degree of safety, efficiency and performance or quality, and to prevent damage, injury or loss of life [5, 8].

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## Problems

1 In the context of machine element design, explain the meaning of failure and failure mode.

2 Give a definition of wear failure and list the major subcategories of wear.

3 List three most likely failure modes of a bicycle, and explain why each might be expected.

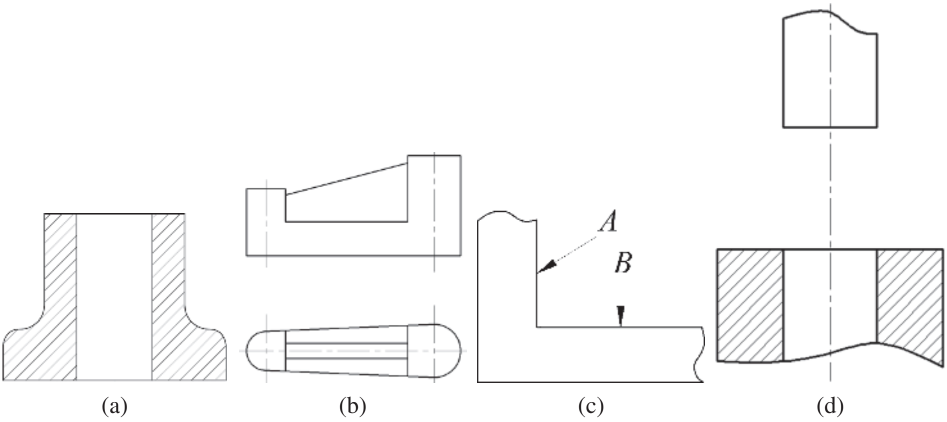

**Figure P1.1** Illustration for Problem 4, four designs that may encounter manufacturing difficulties. (a) Casting. (b) Forging. (c) Heat treatment. (d) Assembly.

**4** The designs in Figure P1.1 may encounter manufacturing difficulties. Find the problems and revise the designs.